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# BOND BEHAVIOR OF POST-INSTALLED REBARS DURING COOLING PHASE AFTER HIGH TEMPERATURE EXPOSURE

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## Abstract

Mortars allow post-installing rebars into pre-existing concrete structures by bonding the steel to the concrete. Post-installed rebars (PIRs) using mortars can offer high mechanical properties at ambient temperatures. However, the mechanical behavior of PIRs, typically governed by the mechanical and physical properties of the mortar, is sensitive to high temperatures. After exposure of PIRs to high temperature, the bond is weakened, and the heat transfer continues during the cooling phase, which endangers the construction after a fire event. This behavior depends on the modification of the PIRs material properties which are temperature dependent. The accuracy of any model-based calculation of the post-fire resistance of such elements depends on the accuracy of the liaison between temperature and the associated material property. Therefore, accurate temperature profiles during the cooling phase are needed to ensure correct calculation of the post-fire behavior of the structure. In order to evaluate the evolution of the load-bearing capacity during fire, (Pinoteau et al. 2013) have developed the bond resistance integration method (Pinoteau's method) to predict the bond resistance variation at different temperatures. Regarding post-fire behavior, design codes do not reproduce the behavior of PIRs during the cooling phase after exposure to high temperatures.

This paper presents an experimental study on post-installed rebars using organic mortars in concrete after exposure to high temperatures. Fire tests were conducted under standard ISO 834-1 fire conditions and constant load, then post-fire pull-out tests were performed at different cooling times at lab temperature by increasing the tensile load applied during the heating phase. This experimental study provides a database for future development of post-fire assessment for design of the load-bearing capacity after high temperature exposure. The assessment procedure needs as entry data the thermal calculations during the cooling phase, and the residual bond-strength temperature relationship.

**Keywords:** *Post fire, Concrete, post installed rebars, Pull-out tests, Bond strength.*

## 1. Introduction

In recent years, there has been a growing interest in using anchoring systems in reinforced concrete structures. Thus, anchorage systems for reinforcement applications are classified into two main categories: "Cast-in place rebars" and "post installed rebars (PIRs)". PIRs are very popular in the strengthening of concrete structures in construction projects. They offer a viable method for adding new concrete sections or attaching steel members to existing structures (Van Gemert 1980) and provide the flexibility in the construction sequence. According to the bonding agents used for PIR applications, PIRs can be divided into two groups (Needham et Juntunen 1998): "organic PIRs" where the bonding agent is organic such as epoxy, polyester and vinylester mortars, and "grouted rebars" where the bonding agent is inorganic such as cement grouts. In order to compare the mechanical behavior between the various existing anchorage systems, (Spieth et al.) had carried out a series of pull-out tests on cast-in place rebars, organic PIRs bonded with epoxy and polyester mortars and on hybrid PIRs bonded with a

combination of vinyl ester and cementitious compounds. Results showed that the hybrid system had a mechanical behavior closest to a cast-in place rebar. While organic PIRs bonded with epoxy mortar showed a larger bond strength and a much higher stiffness than cast-in-place rebars, the organic PIRs bonded with polyester mortar showed a softer behavior and a significant lower bond strength than all other systems. The load-transfer between the rebar and the concrete in post-installed rebars made with mortars is achieved through shearing along the entire bond length (Upadhyaya et Kumar 2015).

The mechanical properties of PIR's made with mortar is governed by several parameters such as materials, geometry and installation procedure (Çolak 2007), (Çolak 2001), (Bingöl et Gül 2009). PIRs have high mechanical properties at ambient temperature, however, for the majority of the mortars used in PIRs, when exposed to high temperatures, the bond resistance decreases. The material properties undergo major changes, particularly, the material strength and stiffness change with increasing temperatures. (Lahouar 2017) showed that the mechanical properties of PIRs made with organic mortars increase when the bond temperature is up to values below the organic mortar glass transition temperature due to the mortar post-cure phenomenon. Whereas, when temperature exceeds the organic mortar glass transition temperature, a change in the viscoelastic properties of the polymer occurs, which results in creep and high sensitivity to temperature (Tavares et al. 2002) (Elalaoui et al. 2012). (Pinoteau 2011) studied the influence of the increase of heating rate on bond failure of post-installed rebars made with mortar in concrete using organic mortars, and concluded that a new bond stress distribution is obtained due to the thermal gradient along the steel rebar caused by the increase of the heating rate. Previous pull-out tests at high temperature have shown that bond capacity decreases rapidly with temperature (Pinoteau 2011), (Lahouar 2017). (Al-Mansouri et al. 2019) have studied the influence of testing conditions for evaluating anchors in concrete under fire on the evaluation of pull-out strength of bonded anchors. A design method at high temperature was developed allowing to predict the time of collapse of post-installed rebars using thermal calculations and bond resistance variation at different temperatures (Pinoteau et al. 2013) (Pinoteau's method). (Lahouar et al. 2018) also proposed a non-linear shear lag model taking into account the displacement compatibility of PIRs made with organic mortars at high temperature in the design process (Lahouar's shear-lag model). Both approaches yielded accurate predictions of fire resistances. However, scarce are the studies that have been carried out to establish the behavior of PIRs during the cooling phase after exposure to high temperatures.

Post installed rebars may fail in different failure modes under tensile loading: concrete cone failure, steel failure, pull-out failure and splitting failure. This paper focuses on the pull-out failure mode. It presents an experimental study to investigate the bond behavior of PIRs made with organic mortars during cooling phase after high temperature exposure. The experimental protocol was divided into two parts: firstly, fire tests were carried out for exposure of 90 min according to the specifications of (EOTA TR 020 2005), on post-installed rebars made with organic mortars, installed as anchors in reinforced concrete beams (1200 mm × 300 mm × 400 mm) with standard ISO 834-1 fire conditions using a gas furnace at the fire resistance laboratory at CSTB. Then, post-fire pull-out tests were conducted at several cooling times through confined tension, displacement controlled tests in accordance with (TR 048). The aim of these tests is to understand the thermomechanical behavior of PIRs made with organic mortars during the cooling phase and to provide a database for a post-fire design method, based on Pinoteau's Method (Pinoteau et al. 2013). This paper shows the experimental post-fire failure loads, and a comparison between the experimental and calculated bond resistances using Pinoteau's method.

## 2. Materials and experimental procedure

### 2.1. Description of test materials

Fire tests were carried out on 6 reinforced uncracked concrete beams of 300 mm of width, 1200 mm of length and 400 mm of thickness. The fire tests were conducted on post installed rebars of 16 mm diameter (GEWI type), using epoxy-based mortar. The PIRs were anchored in concrete with 155 mm ( $\pm 3$ mm) embedment depth. The hole was drilled to the required embedment depth with a hammer drill set in rotation-hammer mode with a medium size cutting diameter  $d_{cut,min}$ . The composition of the concrete used for the manufacturer of beams is presented in Table 1. Characterization tests were carried out on cubic concrete samples (150 mm × 150 mm × 150 mm) after 29 days of curing under ambient

temperature and moisture conditions. The concrete used for casting was a C20/25, it showed a compressive strength equal to 25.8 MPa and a density equal to 2207 kg/m<sup>3</sup>.

Designation	Mineralogical nature	Quantities [kg/m <sup>3</sup> ]
G 0/6.3 Sand	Silico-Limestone	880
G 4/14 Gravel	Silico - Calcareous	792
G 4/22.5 Gravel	Silico - Calcareous	88
<b>CEM II/B-LL 32.5R CE CP2 NF</b>	-	320
Water	-	227

Table 1: Composition of concrete used for casting of beams

The ultimate tensile stress value and the yield stress value of the rebars were also determined ( $f_{u,test} = 670$  MPa,  $f_{y,test} = 577$  MPa). The steel failure of the used GEWI rebar occurred at 135 kN.

## 2.2. Description of the test set-up

Fire tests were conducted at the fire resistance laboratory at CSTB according to the specification of (EOTA TR 020, 2005). Two PIRs were installed on one side of each reinforced concrete beam, one of which was mechanically loaded, while the other was equipped with type K thermocouples along the embedment depth to measure the temperature profiles of the PIR at the steel/mortar interface. The PIRs were anchored in the concrete beams with the epoxy based mortar in beams B1 to B6 as in Table 2. The beam was then placed on a gas furnace with PIRs on the fire exposed surface. The fire exposed surface of the beam was 600 mm × 300 mm. The distance between the loaded PIR centered above the furnace and the unloaded PIR was equal to 150 mm. This aimed to replicate the same temperature profiles of the unloaded PIR in the loaded counterpart, where no thermocouples were positioned to avoid influencing the adherence between the mortar and the rebar. During exposure to fire conditions, the PIRs were loaded in tension under a constant load that represents 4,5% of the resistance at ambient temperature for the mortar. Linear Variable Differential Transformer (LVDT) sensors were used to measure the rebar displacement as presented in Figure 1.

The loading system during the heating phase used hydraulic jacks powered by hydraulic pumps, applying a downward mechanical load (presented by F in Figure 2) on a system of metallic frame surrounding the reinforced concrete beam, and connected to the fixture of the post installed rebar inside the furnace. Details of the used fixtures were adopted from (EOTA TR 020 2005). The steel of the loading system was insulated using a ceramic wool based material in order to protect the steel from reaching failure instead of pull-out (bond failure). The same thermal boundary conditions were applied on both loaded and unloaded PIR. The influence of the loading system on temperature profiles and resulting load bearing capacity of bonded anchors in the heating phase were investigated by (Al-Mansouri et al. 2019) (Al-Mansouri et al. 2020) and found negligible.

Afterward, the test specimen was exposed to 90 min of heating under ISO 834-1 fire using the gas furnace. The temperature increase rate being higher while using a gas furnace instead of electrical heating, a thermal gradient along the bond was obtained. The heating time was chosen in a way that the maximum temperatures along the bond would be lower than 300°C. This temperature was selected because most mortars typically provide bond strengths lower than 1 MPa beyond this value according to characterization tests in (« EAD 330087-00-0601 » 2018), due to the loss of adhesion and the carbonization of the mortar that only resists in friction beyond this temperature. In order to obtain a post-fire bond failure, this maximum temperature at the steel/mortar interface was considered in the design procedure of the tests to guarantee that the failure occurs during the cooling phase instead of during the heating phase, and to prevent steel failure in the tests. Afterwards, the test specimen was removed from the oven and left to cool down for several cooling times as presented in Table 2.

The next step consisted of conducting the post-fire pull-out tests at the different cooling times with tension loading and confined test setup to prevent concrete cone failure, where the loading was displacement controlled. Figure 1 shows the testing apparatus during heating, where the reinforced concrete beam was placed on the gas furnace, and the testing apparatus (confined tension test) after fire exposure in the cooling phase.



Figure 1: Testing apparatus in the heating phase (Left) and the cooling phase (Right)

Specimen	Cooling time after exposure to fire conditions
B1	50 min
B2	50 min
B3	2h
B4	3h 40 min
B5	3h 40 min
B6	24 h

Table 2: Post fire tests configuration

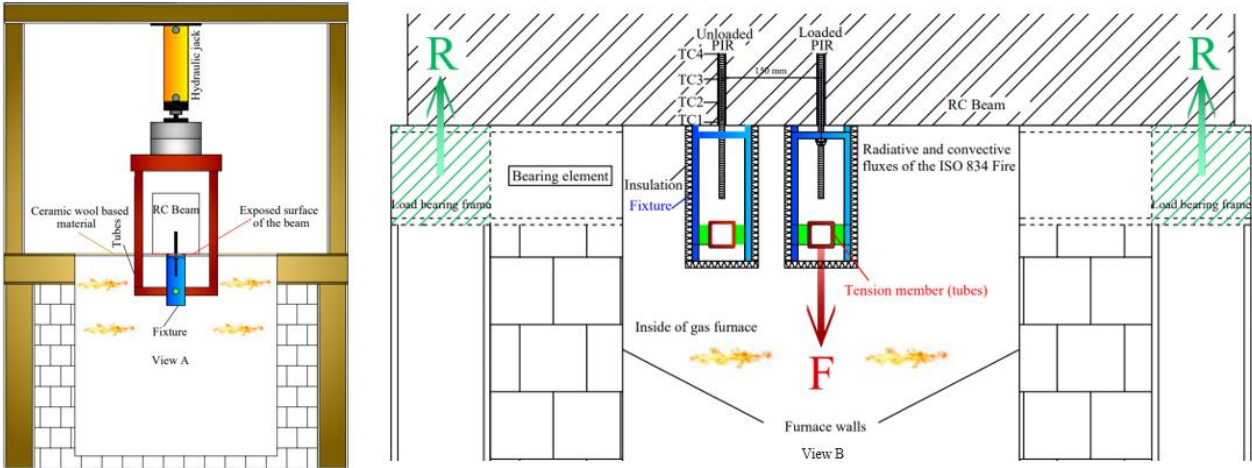


Figure 2: View of the gas furnace and the loading system during the heating phase

### 3. Results and discussions

#### 3.1. Experimental post-fire failure loads

The results of post-fire pull-out tests according to the cooling time are shown in Figure 3, the experimental obtained bond resistances were normalized, where 1 corresponds to the reference bond resistance at ambient temperature for a specimen never heated. Results suggest that the load bearing capacity of this epoxy-based mortar increases with cooling time, indicating a probable strength recovery of this mortar during the cooling phase. It is pointed out that the failure mode obtained during post fire tests was pull-out failure at the steel/mortar interface, except for cooling times of 3h:40 min and 24h, where bond failure caused by steel elongation for the former and steel failure for the latter case were observed.

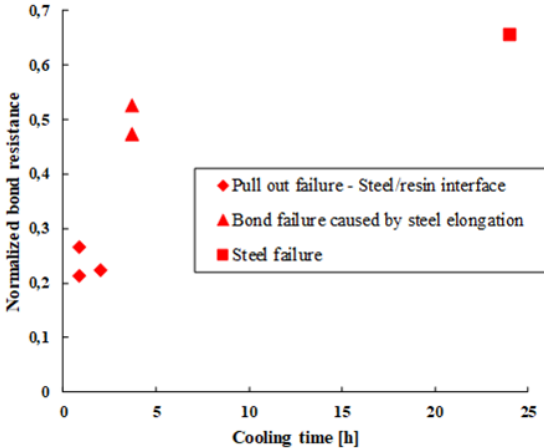


Figure 3: Post-fire pull-out normalized resistances at different cooling times

#### 3.2. Experimentally obtained temperature profiles

The results of experimentally measured temperature profiles at the steel/mortar interface at the end of the heating phase, and at the time of post fire pull-out tests are shown in Figure 4. Regarding the obtained temperature profiles at the end of the heating phase, steep thermal gradients along the PIRs were observed near the heated surface of concrete beams, while thermal gradients were lower in the inner depths of the specimens. Furthermore, it is shown that almost constant temperatures at the time of post-fire tests were observed for the different cooling times after exposure to fire conditions. Figure 5 presents an example of the evolution of the temperature of thermocouples along the PIR vs. time for the PIR embedded in beam B5. The temperature plateau was caused by the water vaporization, which is an endothermic transformation and consumes part of the energy brought by heating. The temperature increased again once all the moisture evaporated, and continued to rise during the cooling phase to a certain level before cooling down to lab temperature. At the time of the post-fire pull-out tests, the temperatures along the bond were quasi-homogeneous.

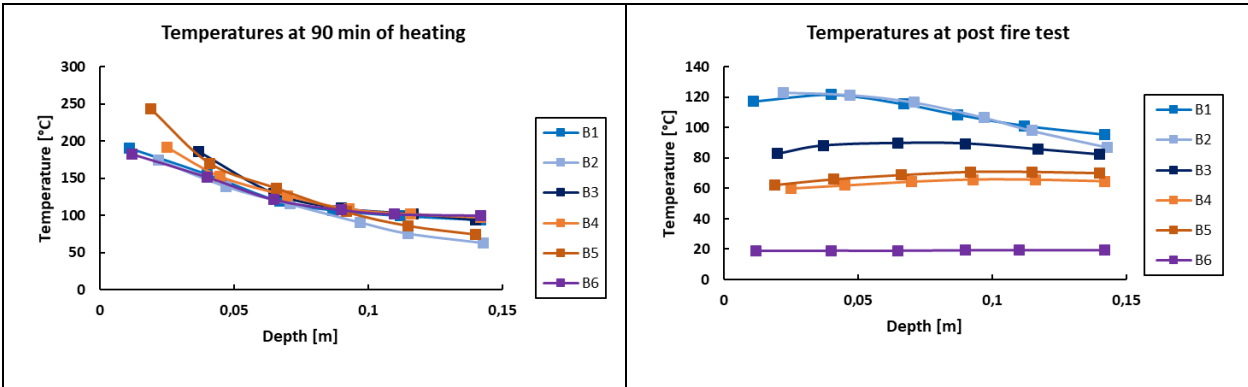


Figure 4: Temperatures of thermocouples vs embedment depth

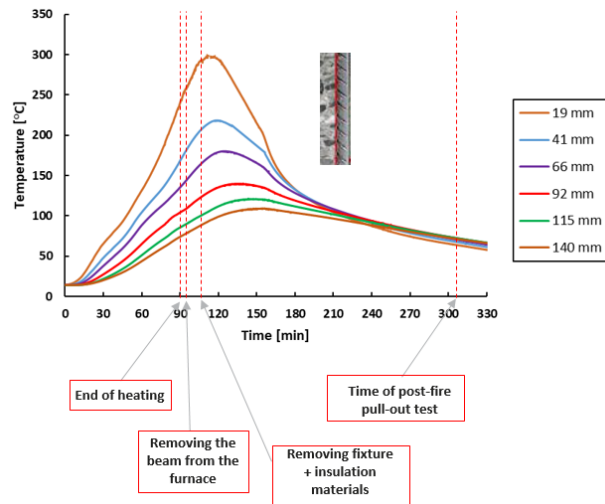


Figure 5: Temperature of thermocouples vs. time for HA16 PIR in B5

### 3.3. Mechanical behavior of PIRs depending on the cooling time

Load v.s displacement curves for the epoxy-based mortar are shown in Figure 6. The results were similar to the results in section 3.1, where the change of the slope was significant for this mortar, indicating higher gain of stiffness with cooling time. It also shows that post-fire load bearing capacity of this mortar increases with cooling time, which can be attributed to a probable strength recovery of this mortar during the cooling phase.

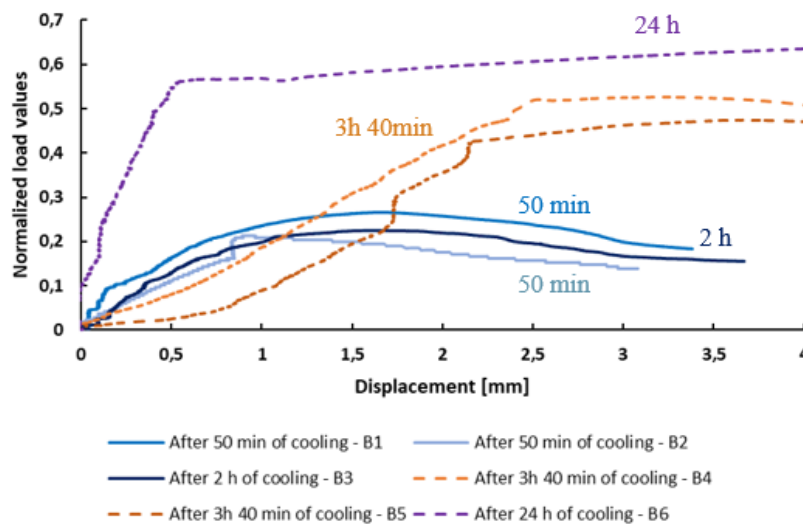


Figure 6: Mechanical behavior of PIRs at different cooling times

### 3.4. Comparison between test results and predicted results using Pinoteau's Method

To calculate the evolution of the bearing capacity of PIRs subjected to temperature variation, (Pinoteau et al. 2013) proposed a "bond resistance integration method" using thermal calculations and bond resistance variation at different temperatures. Pinoteau's method was validated by performing a full-scale ISO fire on a cantilever-wall connection using PIRs made with organic mortars. Pinoteau's method was used in the calculated bond resistances in Figure 7. Hence, the resistance profiles are estimated during the heating and cooling phases by using the experimental temperature distribution recorded during the tests and using the bond resistance vs. temperature relationship available only during the heating phase for this mortar assuming both hypotheses: an irreversible and reversible bond strength degradation during the cooling phase (Residual bond strength characterization tests having not been performed at this time). At the section points where no experimental values of temperature were

available, temperatures were extrapolated through the depth by a temperature vs. depth curve. The bond stress vs. temperature relationship was obtained from tests according to (« EAD 330087-00-0601 » 2018). Figure 7 shows a comparison between post-fire tests and the outcome of Pinoteau’s method for the epoxy-based mortar used in this study. The dashed lines correspond to the calculated resistances during the heating phase up to 90 min, while the continuous lines refer to the calculated resistances during the cooling phase. It is interesting to note that the bond resistances continue to decrease in the first stage of the cooling phase due to the continuous heat diffusion to the cooler parts towards the unexposed surface. It is shown that experimental post-fire pull-out resistances are higher than the calculated resistances. Therefore, for this mortar type and test configuration, Pinoteau’s method underestimates the bearing capacity of PIRs during the cooling phase, which justifies the need to characterize more precisely the bond resistance vs. temperature relationship of PIRs during the cooling phase.

In order to benefit from the recovery of the bond in a post-fire design model, more work is needed to study the reversible degradation of organic mortars at high temperatures.

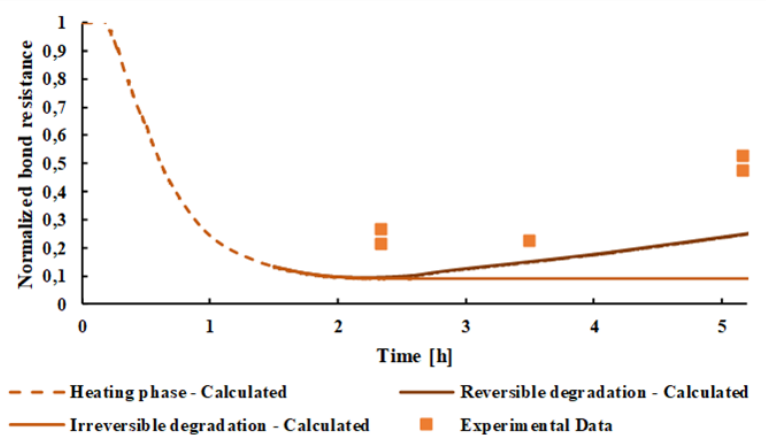


Figure 7: Calculated and Experimental normalized post-fire pull-out resistances of 16 mm PIR with 155 mm  $\pm$  3 mm embedment depth

## 4. Conclusion

This paper aimed to provide results and preliminary information on the evolution of the load bearing capacity of PIRs made with organic mortars during the cooling phase after exposure to ISO 834-1 standard fire conditions, by conducting post-fire pull-out tests. These tests were conducted on PIRs installed in reinforced concrete beams using an epoxy based mortar. Tests were conducted at different cooling times. The experimental results showed that post-fire pull-out resistance increases with cooling time (23% and more than 50% of the resistance at ambient temperature were respectively obtained at the lowest and highest cooling time). This conclusion can be associated to a probable strength recovery of the epoxy based mortar during the cooling phase.

The comparison between test results and calculated results using Pinoteau’s method showed that the latter underestimates the bearing capacity of PIRs during the cooling phase for this mortar type embedded with 155 mm  $\pm$  3 mm embedment depth. The variation of temperature profiles during the cooling phase has been shown to have a significant influence on the post-fire resistance of PIRs.

The results of this paper establish the need for additional investigations and research to develop a more rational characterization of the bond resistance vs. temperature relationship of PIRs during the cooling phase as basis for a safe and reliable post-fire design concept.

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